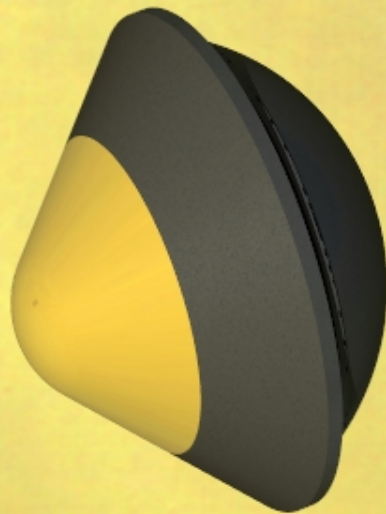
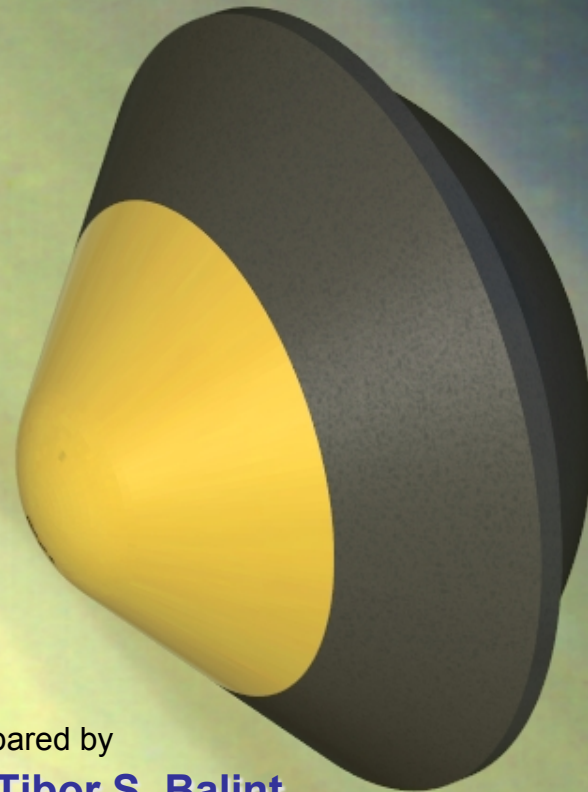


SATURN PROBE MISSION FEASIBILITY & TRADES

BASED ON
NASA FUNDED STUDIES



Prepared by

Dr. **Tibor S. Balint**

JPL/Caltech

Presented at the

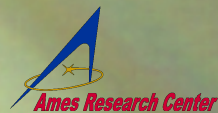
5TH INTERNATIONAL

PLANETARY PROBE WORKSHOP

IPPW5

BORDEAUX, FRANCE

June 23-29, 2007





FY06 Saturn Probes Study Team (SPST):

- Doug Abraham – DSN / Telecom (JPL)
- Gary Allen – Probe descent (Ames)
- Dave Atkinson – Science (U of Idaho)
- Tibor Balint – *Study lead*, Architectures, Power (JPL)
- Rob Carnright – Trajectory visualization (JPL)
- Bill Folkner – Telecom, Architectures (JPL)
- Sergey Gorbunov – Probe CAD (NASA Ames)
- Helen Hwang – TPS, costs (NASA Ames)
- Anil Kantak – Telecom (JPL)
- Theresa Kowalkowski – Trajectories (JPL)
- Try Lam – Trajectories (JPL)
- Ed Martinez – TPS, costs, E/D (NASA Ames)
- Dave Morabito – Telecom (JPL)
- Bill Smythe – Science, Instruments (JPL)
- Tom Spilker – Architectures, Attenuation, Science (JPL)
- Nathan Strange – Trajectories, Architectures (JPL)
- Bill Strauss – Probe entry / descent (JPL)
- Mike Tauber – TPS, E/D (ELORET Corporation)

2006 Planetary Science Summer School, Team-2 (PSSS-2):

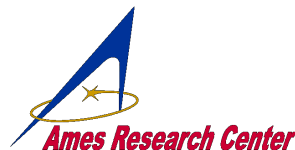
- Aubrey Watson (Project Manager),
- Shadrian Strong (PI),
- Olivia Dawson (Probe Co-I),
- Justin Likar (Fly-by Co-I),
- Andrew Aubrey (Science),
- Nathan Bramall (Thermal),
- Andrew Chereck (Instruments),
- Gerardo Dominguez (Power),
- Eric Hultgren (Structures),
- Joseph Levy (Cost),
- Thomas Liu (Propulsion/Attitude Control),
- Megan Madden (Ground Systems),
- Catherine Plesko (Telecom),
- Deborah Sigel (Structures & Configuration),
- Yuki Takahashi (Systems Engineering),
- Shane Thompson (Software/Science),
- Krista Soderlund (CDS),
- Bradley Thomson (Risk/Programmatics),
- David Wiese (Mission Design)

PSSS Mentor & Administrative Support (JPL):

- Tibor Balint & Anita Sohus, CoCo Karpinski, Jean Clough

Study Sponsor:

- NASA's Planetary Science Summer School



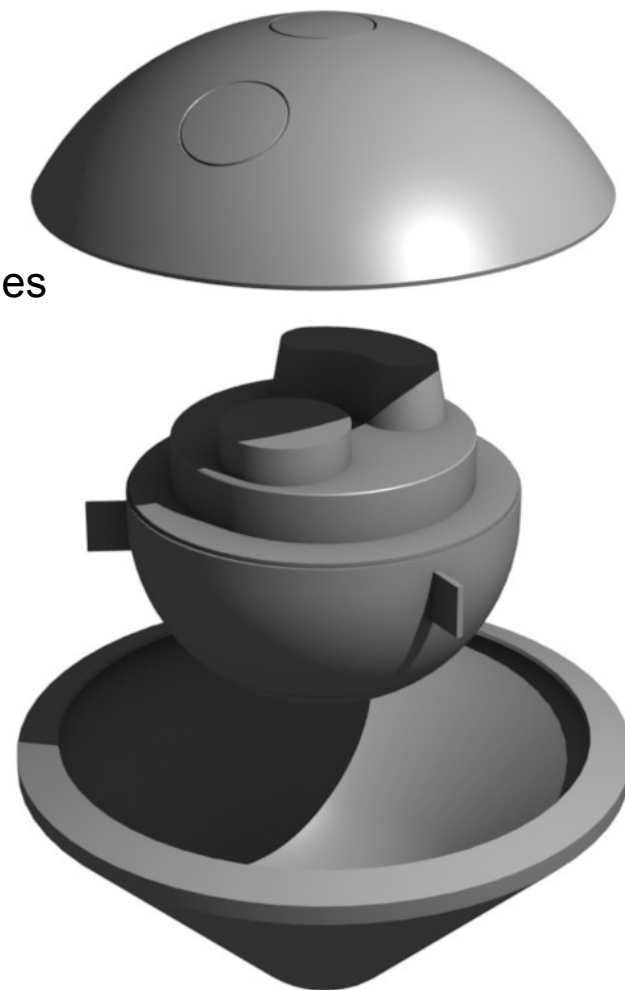
FY06 Study Sponsors:

- Curt Niebur – NASA HQ
- James Cutts – 4X Chief Technologist (JPL)

Additional thanks for their support to:

Jennie Johannesen (trajectories); Sam Gulkis (MWR), Ted Sweetser, Keith Warfield, and Team X

- Science measurement objectives
- Initial assumptions for Saturn multi-probes studies
- Probe and carrier notional science instruments
- Key mission architecture stages & elements
 - Trajectory options
 - Key mission drivers for the carrier s/c
 - Key mission drivers for the probes
- Conclusions & recommendations



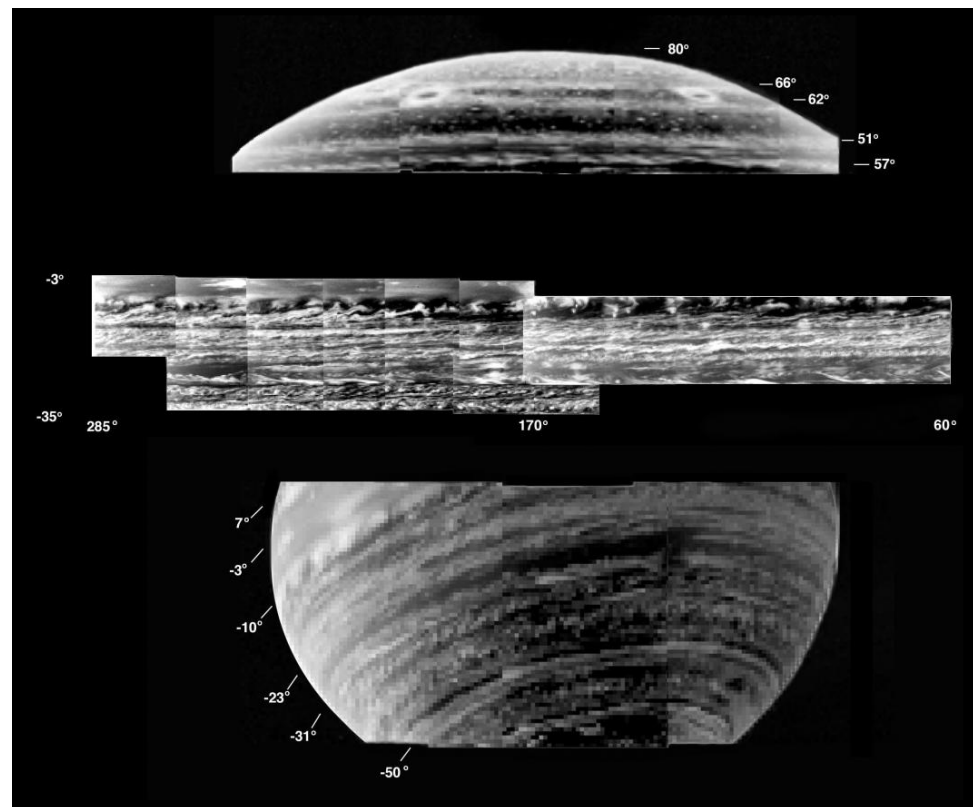
Key: Comparative planetology of well-mixed atmospheres of the outer planets is key to the origin and evolution of the Solar System, and, by extension, Extrasolar Systems (Atreya et al., 2006)

• Origin and Evolution

- Saturn atmospheric elemental ratios relative to hydrogen (C, S, N, O, He, Ne, Ar, Kr, Xe)
- Key isotopic ratios (e.g., D/H, $^{15}\text{N}/^{14}\text{N}$, $^3\text{He}/^4\text{He}$ and other noble gas isotopes)
- Helium abundance relative to solar & Jupiter
- Gravity and magnetic fields

• Planetary Processes

- Global circulation
- Dynamics
- Meteorology
- Winds (Doppler and cloud track)
- Interior processes (by measuring disequilibrium species, such as PH_3 , CO , AsH_3 , GeH_4 , SiH_4)



NASA – Cassini: PIA03560: A Gallery of Views of Saturn's Deep Clouds

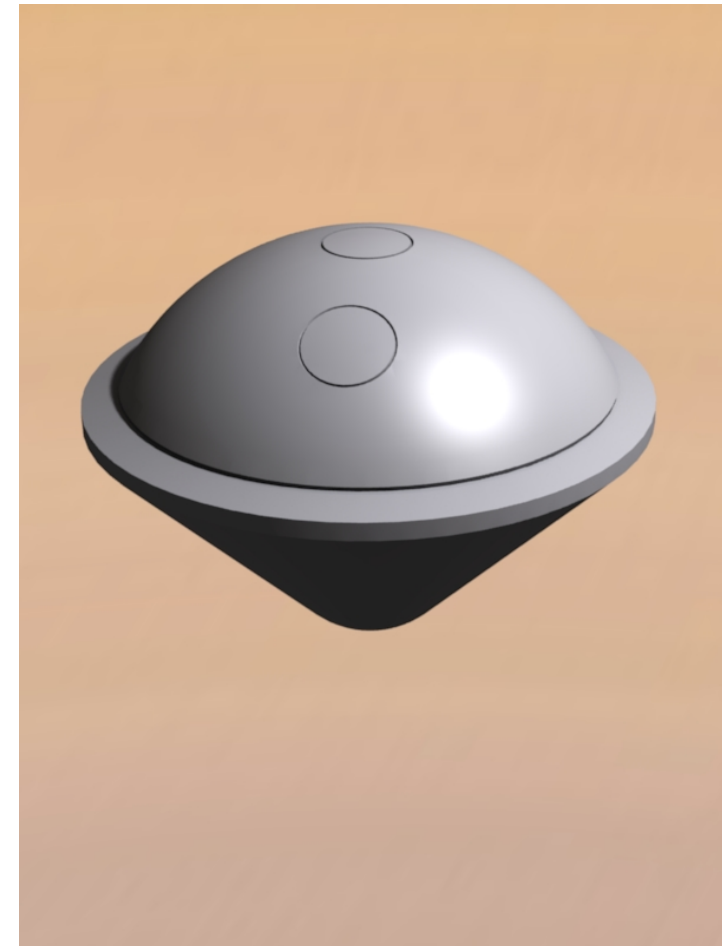
Required → driven by Science Objectives:

- **Two (2) shallow probes to 10 bars**
 - Latitude location: dissimilar regions (zones/belts)
 - E.g., two sides or the $\pm 13^\circ$ Equatorial zone
 - Relay OR Direct-to-Earth communication
- **Microwave radiometry (MWR) to ~100 bars**
 - MWR on carrier
 - Carrier options: Flyby or Orbiter
- **Fields and particles**
 - Saturn's gravity field
 - Saturn's magnetic field

Ref: S. Atreya; T. Balint & FY06 Study Team members

Programmatics:

- **New Frontiers** class mission
 - Cost cap assumptions: today's \$750M
 - Next NF Opportunity: ~ 2015
- **Potential International Collaboration**
 - Cosmic Vision KRONOS proposal

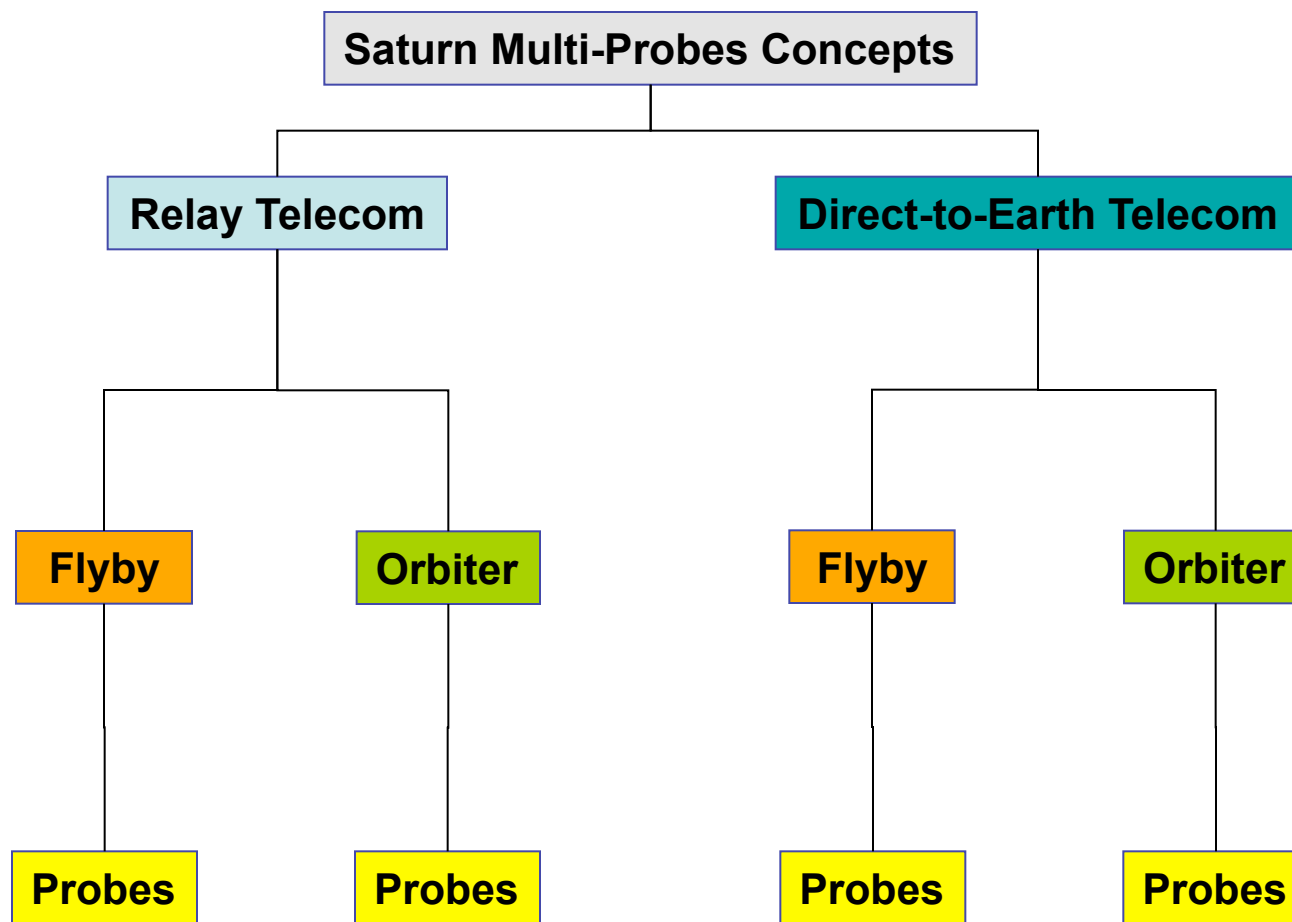


Assumed for Saturn Probes & Flyby S/C in Previous Studies – Galileo Probe Heritage

Shallow Probe to 10 bars	
ASI	– Atmospheric Structure
NEP	– Nephelometer
HAD	– Helium abundance
NFR	– Net flux radiometer
NMS	– Neutral mass spectrometer
LRD /EPI	– Lightning / Energetic particles
ARAD	– Ablation monitor – on TPS
DWE	– Doppler wind experiment
OPH	– Ortho-Para Hydrogen
TLS	– Tunable laser spectrometer
IMG	– Imaging

Carrier: Flyby or Orbiter	
MWR	– Microwave radiometer
GRV	– Gravity mapping
MAG	– Magnetometer
SSI	– Imaging
DWE	– Doppler Wind Experiment

- This **might be** an **oversubscribed** strawman payload set
- The actual number of instruments would be dictated by the final design and mission cost allocation for New Frontiers missions
- In previous studies we assumed the same instrument **sampling rate per distance traveled as used on the Galileo probe** (this will be reassessed based on the telecom option)



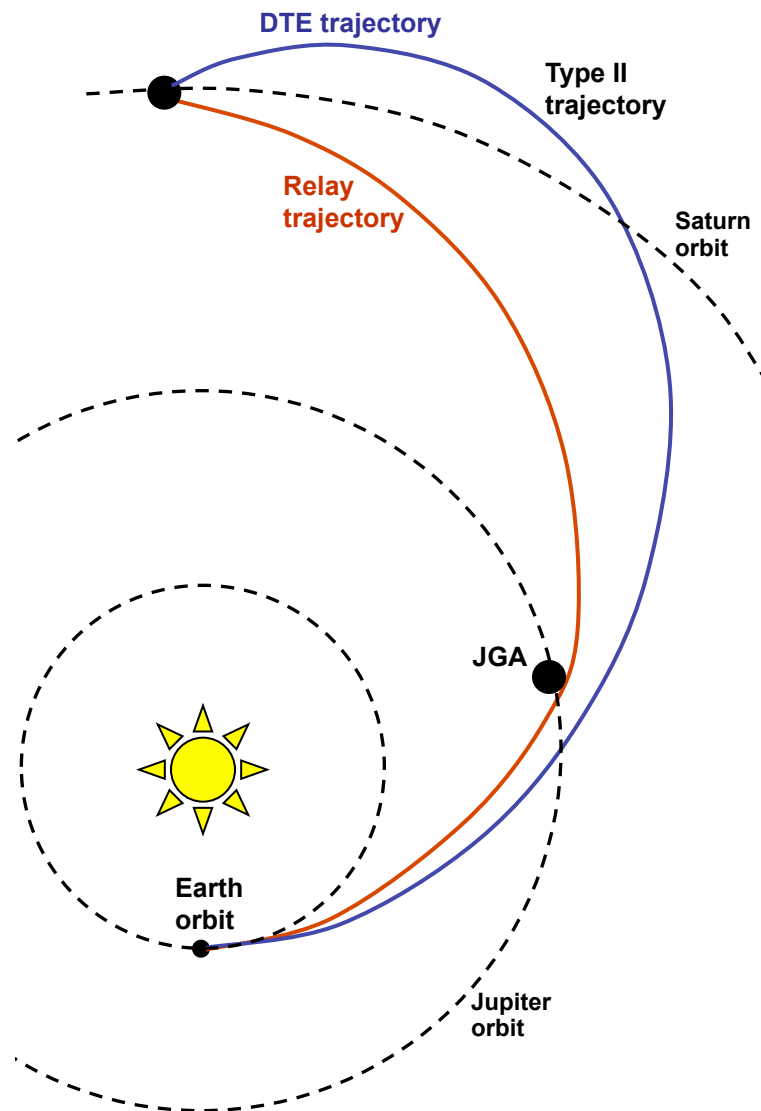
Each of these mission architecture trade option has significant impacts on the mission, with distinct advantages and limitations. There isn't a single best solution yet.

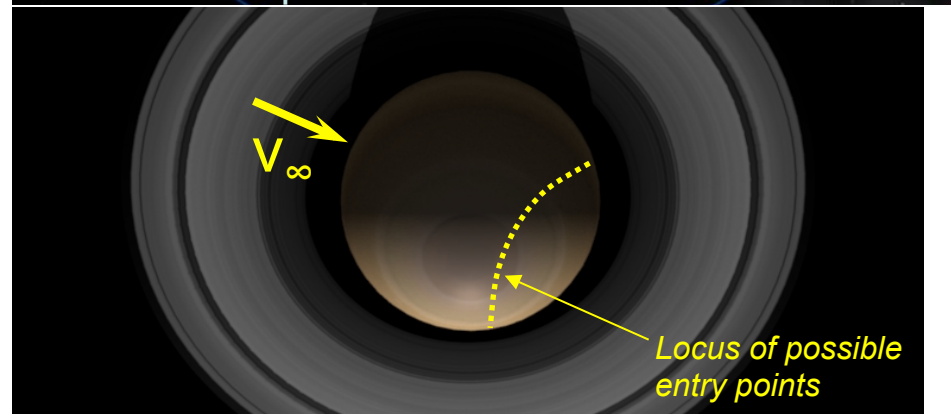
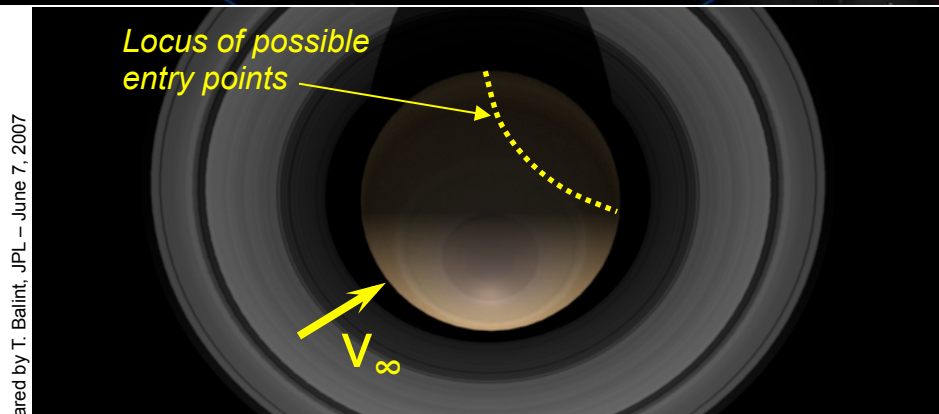
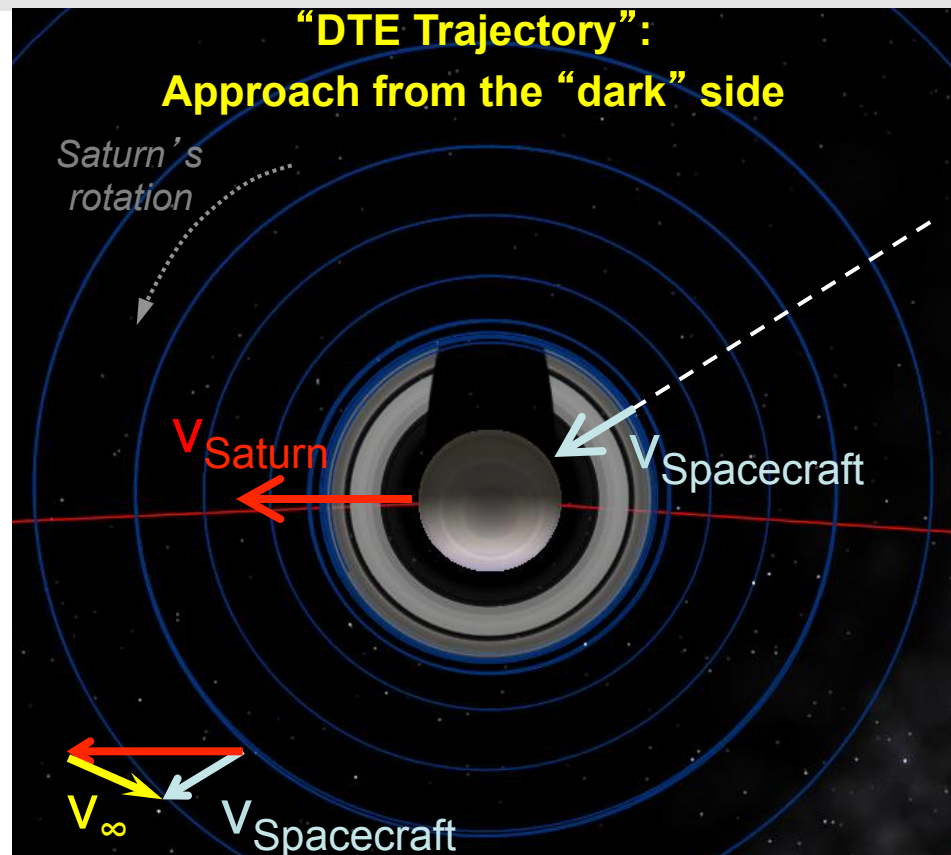
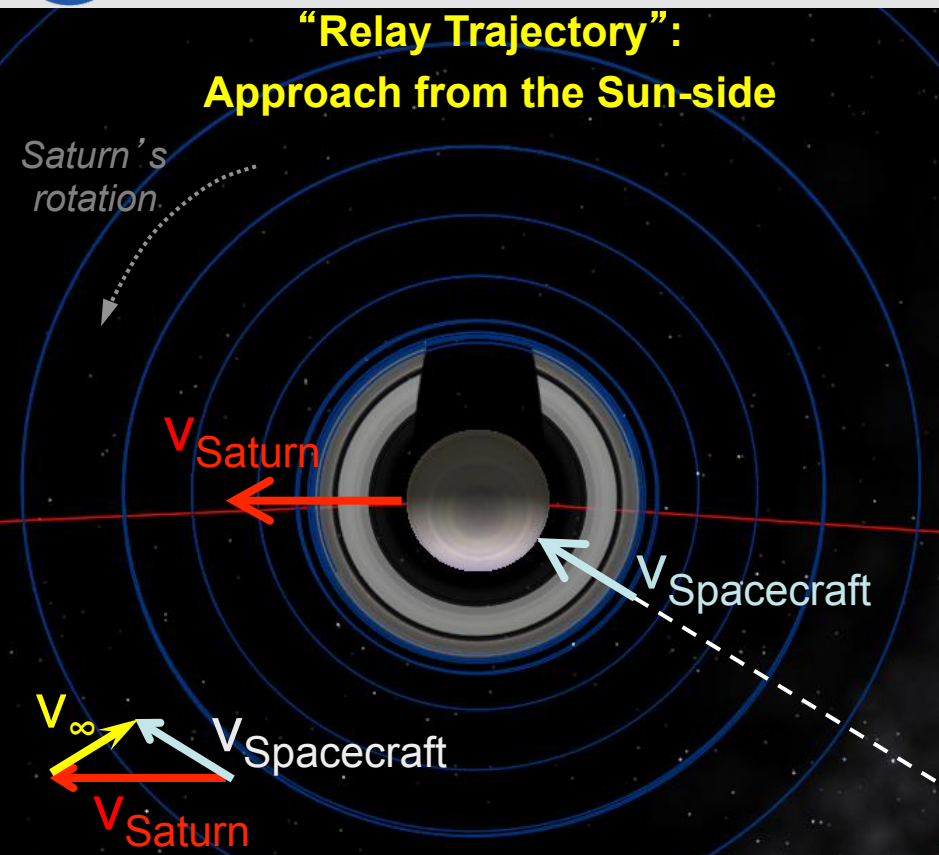


Getting there: Trajectory options

- Trajectory options:
 - **Direct trajectory**
 - delivered mass too low (less than 100 kg)
 - **Gravity Assists**
 - **Inner planets Gravity Assist**
 - Earth & Venus
 - With or without additional (+dV)
 - **Jupiter GA + inner planet(s) GA + (dV)**
 - This option is not available after 2017
 - **Jupiter & Saturn: alignment in every 19 years**
 - » 1978 - 1997 – 2016 – 2035
 - » Last opportunity for JGA: Jan. 2017

- Different trajectory strategies are required for Direct-to-Earth (DTE) and Relay telecom:
 - For **Relay** telecom from probes:
 - Benefit from **Jupiter GA**
 - **Reduced eccentricity**
 - **Shorter trip time, higher delivered mass**
 - Telecom: from probe → to carrier → to Earth
 - **No visibility between probe and Earth!**
 - For **DTE** telecom from probes:
 - **Can't use Jupiter GA;**
 - **Type II trajectory** for **DTE probe access**
 - **Longer trip time** to achieve suitable probe trajectory for DTE telecom
 - Telecom: Visibility to Earth for DTE link



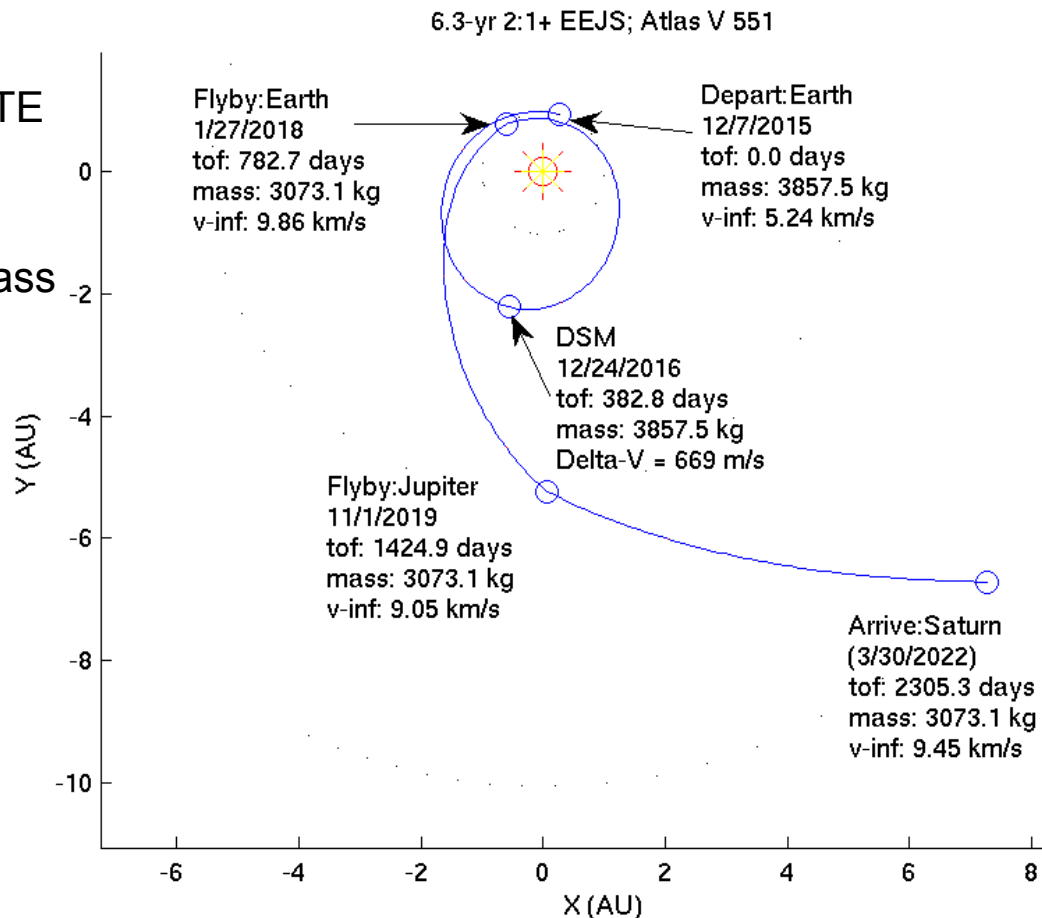


- Representative baseline trajectory
 - EEJS; ~685 m/s DSM
 - December 2015 Launch
 - ~6.3-yr flight time
 - Probes enter on the dark side – No DTE
 - Supports Relay telecom option
 - SEP option → delivers ~30% more mass

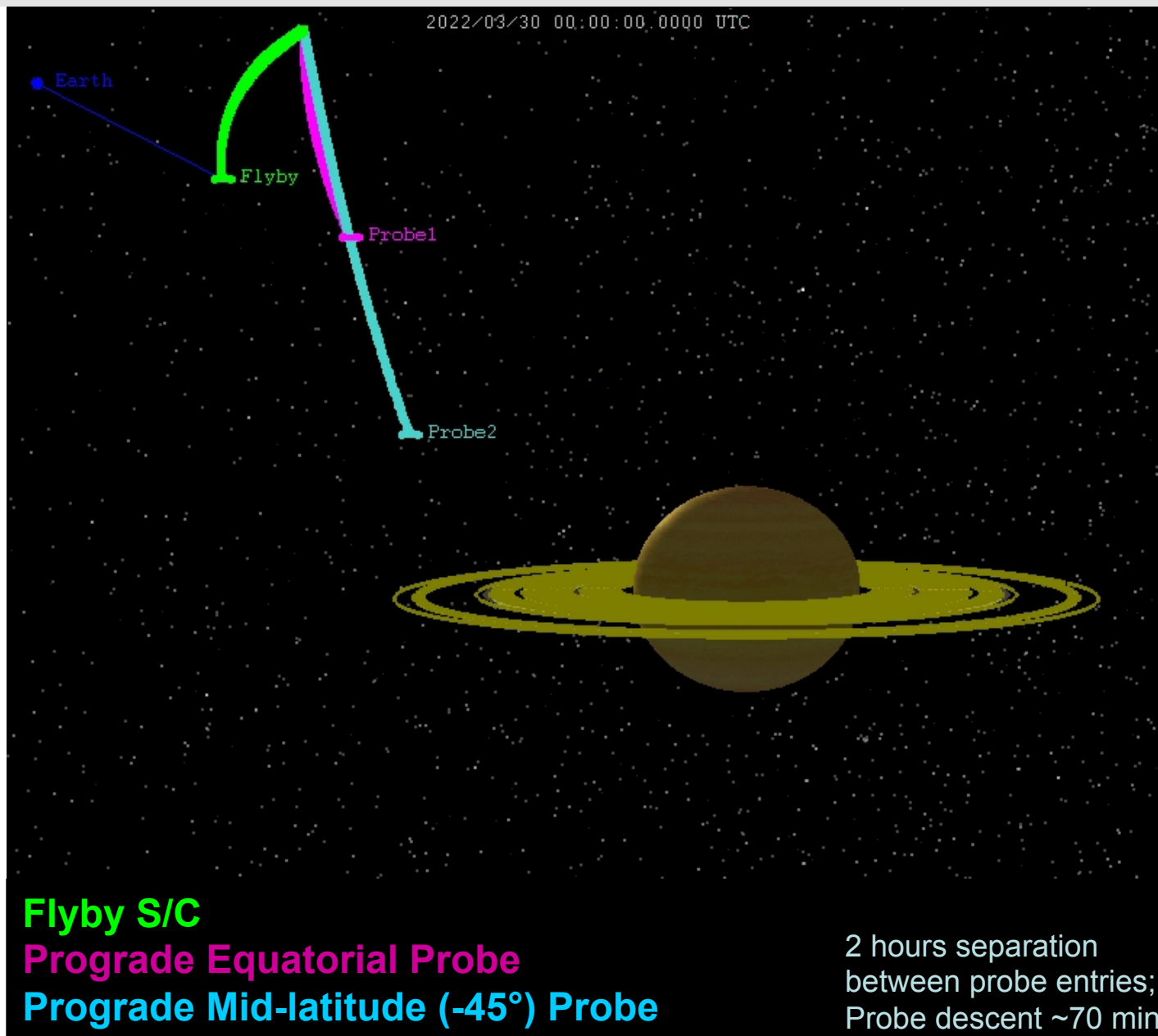
Launch Vehicle	Delivered Mass*
Delta IV - 4050H	4411 kg
Atlas V - 551	3073 kg
Atlas V - 521	2124 kg
Atlas V - 401	1566 kg
Delta IV - 4040-12	956 kg



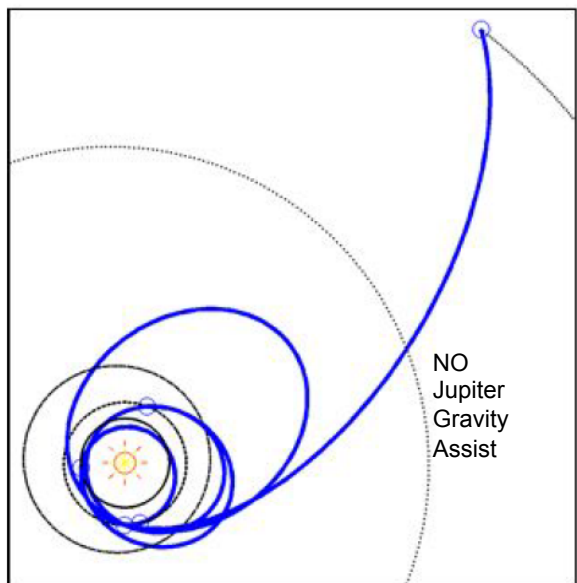
*Deterministic and optimal performance values; does not include statistical estimates or a 21-day launch period analysis



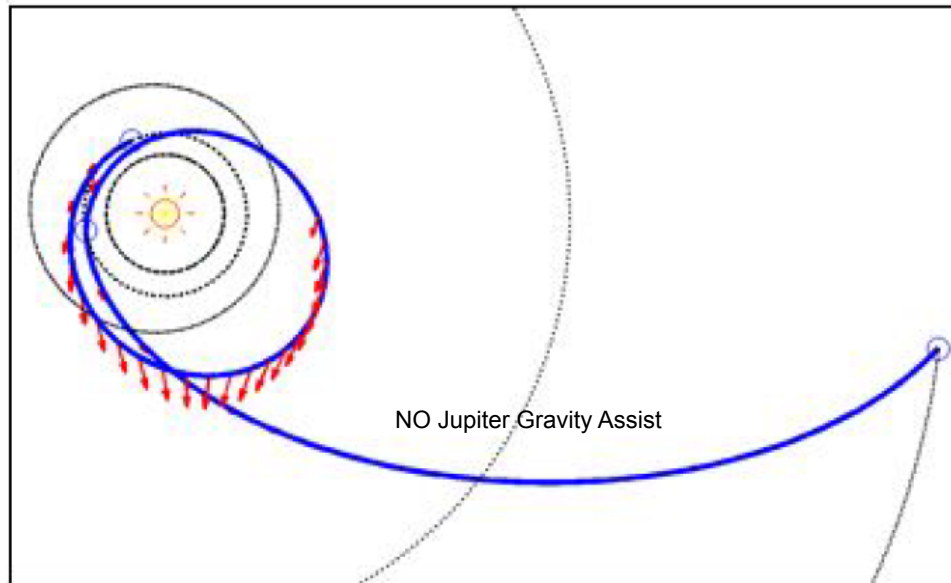
Point design could result in a smaller Launch Vehicle, thus reducing cost



Pre-decisional – for discussion purposes only



Example **Chemical** Trajectory to Saturn
Flight time **>9 years**



Example **Solar Electric Propulsion** Trajectory to Saturn
Flight time **~ 6 years**

BUT,

- These trajectories will not get the probes close to the sub-Earth point!
- For that **we need a Type 2 trajectory**, which could **increase the flight** time by about and estimated 2 to 6 years (TBD)
- Longer flight times are required to reach **optimal sub-Earth point** for Direct-to-Earth telecom
- **Non-optimal off-sub-Earth point could impact telecom / feasibility**

Ref: Kim Reh, "Titan and Enceladus \$1B Mission Feasibility Study Report", JPL D-37401 B

- **Ring Crossing:**

At Clear gaps, e.g., between rings F & G; or inside the D-ring are considered lower risk

- **Ring Collision:**

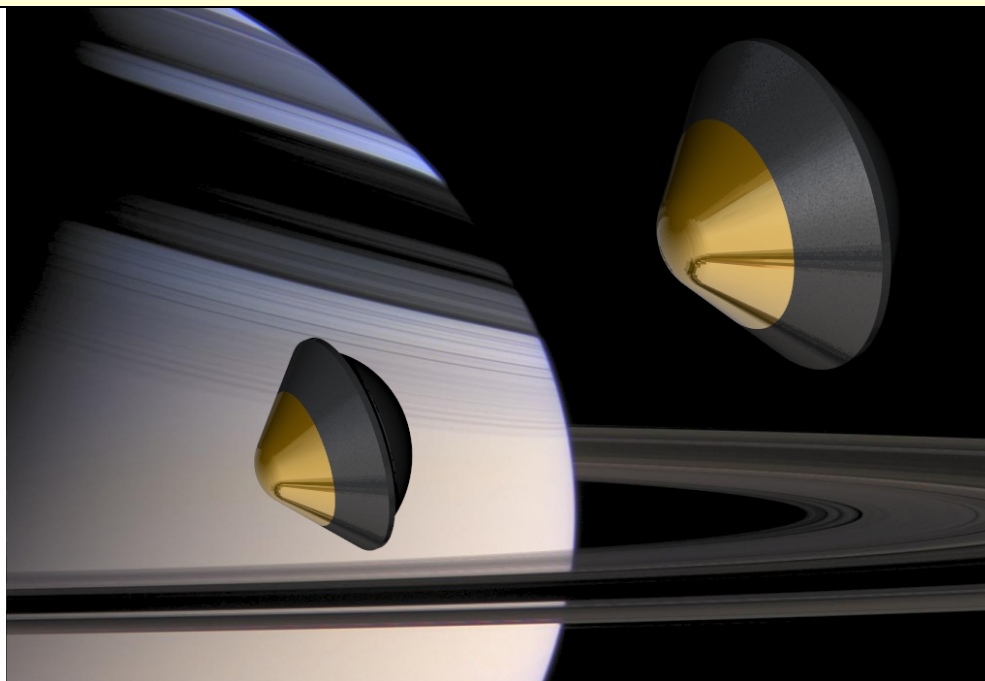
Juno-like elliptic orbit: would precess faster due to Saturn's obliqueness

- **Flyby missions:**

Lower risk: require one ring crossing

- **Orbiter missions:**

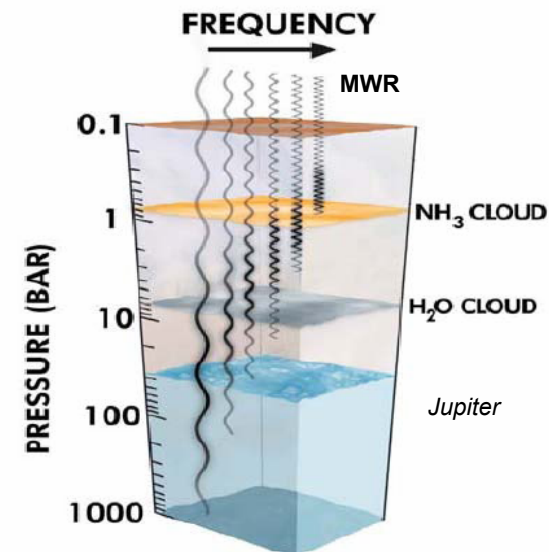
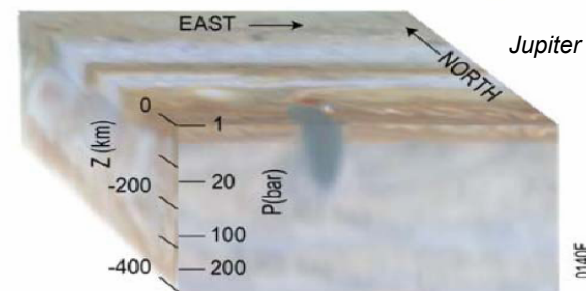
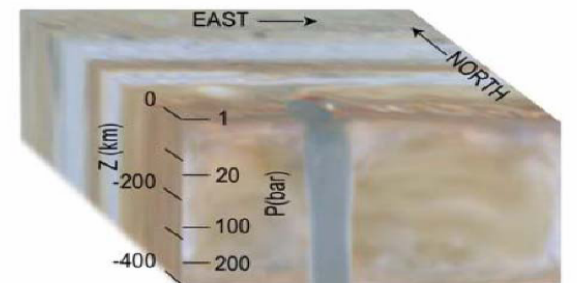
Higher risk: require multiple orbits / ring crossings



Pre-decisional – for discussion purposes only

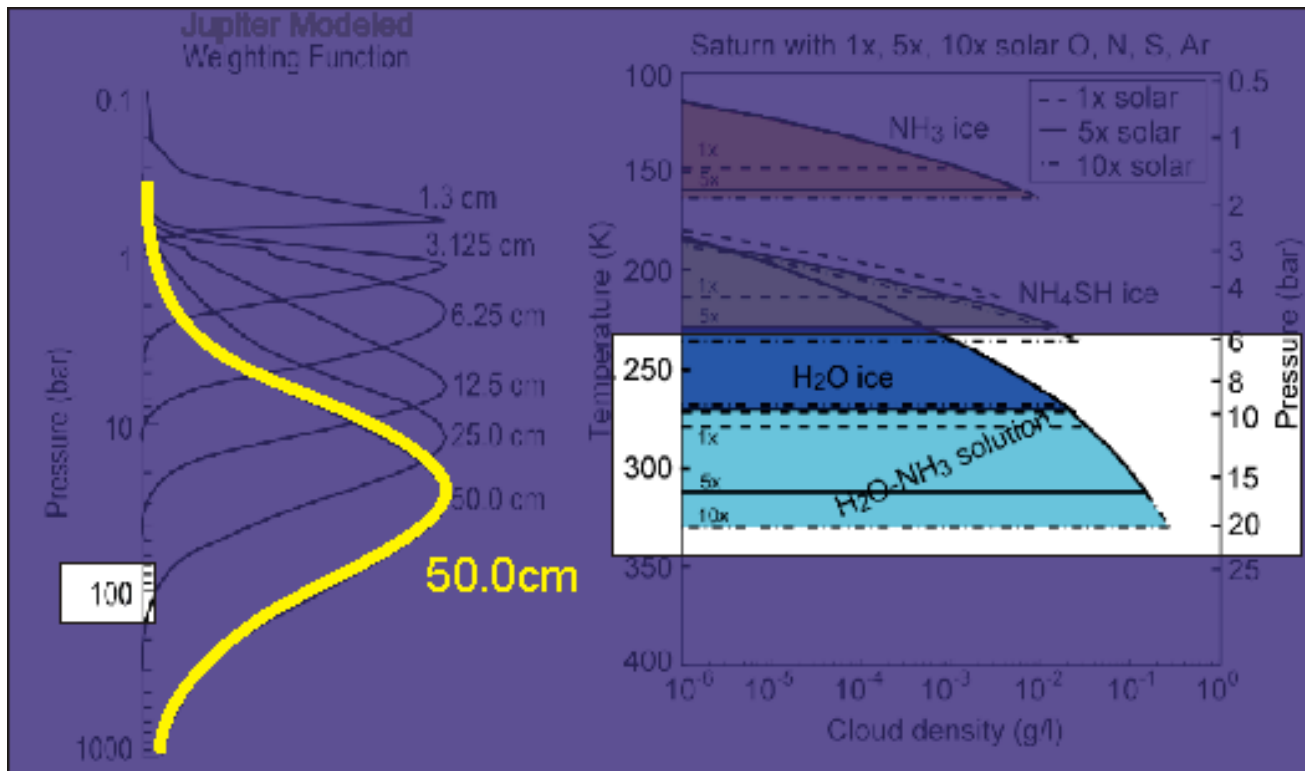
Key Mission Drivers for the Carrier Spacecraft

- **Close proximity to Saturn** is **required** for effective MWR measurements:
 - E.g., Juno performs MWR measurements from 60,000 km to 4,000 km
 - The **studied architectures are too far** (~100,000 km to ~200,000 km when crossing between F & G gap)
- **Perpendicular spin to flight direction** is **required** (Juno operational heritage)
 - For scanning sky, limb & atmosphere
 - For scanning same cloud location from various angles
 - **Spinning probe mounted MWR do not satisfy this**
- **Polar flyover** is **desirable** (but not necessary)
 - Polar flyover or flyby allows for magnetometer measurements (**desirable**)
 - **Studied architectures do not satisfy this**
- **Multiple MWR measurements** are **desirable** (but not necessary)
 - This would **require an orbiter**



Ref: Scott .J. Bolton, Tristan Guillot, Michel Blanc, & the JUNO team, Juno Presentation Juno Presentation to the SSWG to the SSWG, April 20th, 2006, ESA HQ, Paris Page: 17

- Primary science goal: → measure water abundance to 100 bars
- Microwave radiometry: → remote sensing of H_2O , NH_3 (hard to separate)
- **MWR antenna size:** NOT KNOWN; must be resized for Saturn
- **Weighting functions:** NOT KNOWN; must be recalculated for Saturn
- **Environment:** No Radiation at Saturn simplifies MWR compared to Jupiter
- **Heritage:** Similar instrument will fly on **Juno**, but here a new design is required



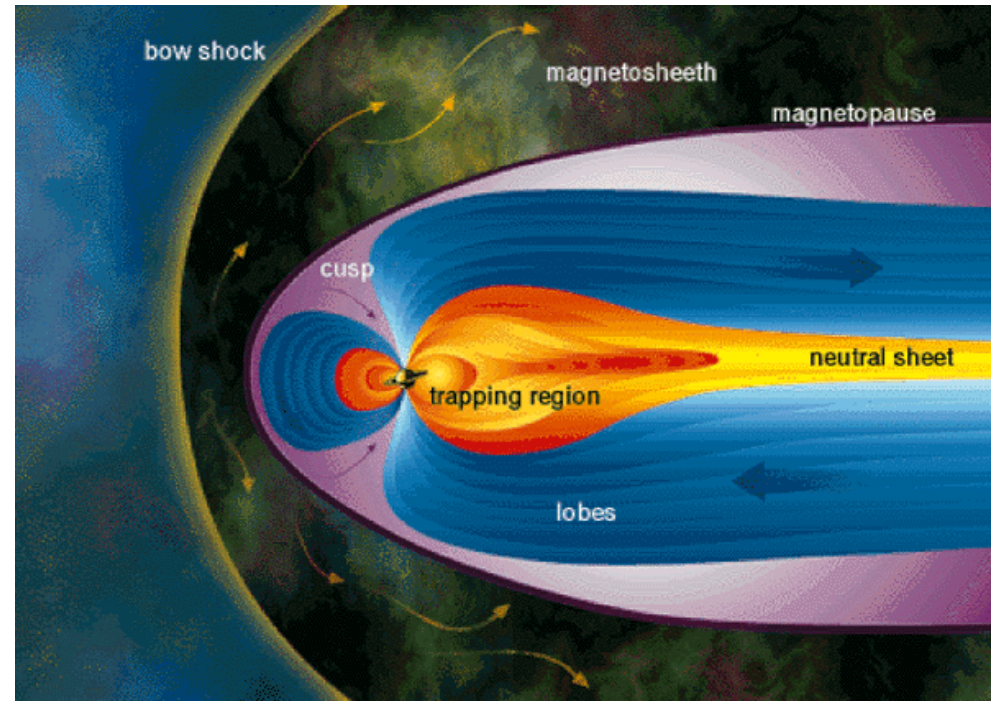
Ref: Gulkis, S., and Janssen, M. (2005)

Ref: Atreya, S. (2006)

Ref: PSSS-2 (2006)

Pre-decisional – for discussion purposes only

- Magnetic field and magnetospheric measurements:
 - Science priority drives the inclusion of these measurements
- Magnetic and gravity field lines:
 - Polar trajectory is required
 - Orbiter → multiple pass → desirable, but mission impacts (e.g., complexity, cost)
 - Flyby → single pass only → limited science benefit
- Inner radiation belt:
 - Near equatorial trajectory, with less than 30° inclination



Passing through **field lines**:

- **DTE** architecture **suitable**: decouples probes and carrier
- **Relay** architecture alone: does not support polar flyby

Inner radiation belt:

- **Relay** architecture: **suitable**, simple, short cruise
- **DTE** architecture: **not suitable** if targets polar flyby/orbiter trajectory

- **Solar Panels on a flyby s/c with relay telecom**
 - **Before Saturn:**
 - Solar panels would generate power during cruise
 - Operation: checks in every 3 weeks, when operating from solar power and secondary batteries
 - **At Saturn:**
 - Flyby s/c science operations would be ~6 hours near Saturn (telecom and MWR on carrier)
 - Preliminary studies indicate that this could be done with primary batteries; i.e., solar panels are not required for this operational phase
 - **After Saturn:**
 - If collected data is not down-linked during a single pass using batteries, the solar panels could trickle charge the batteries and send the data back in subsequent passes

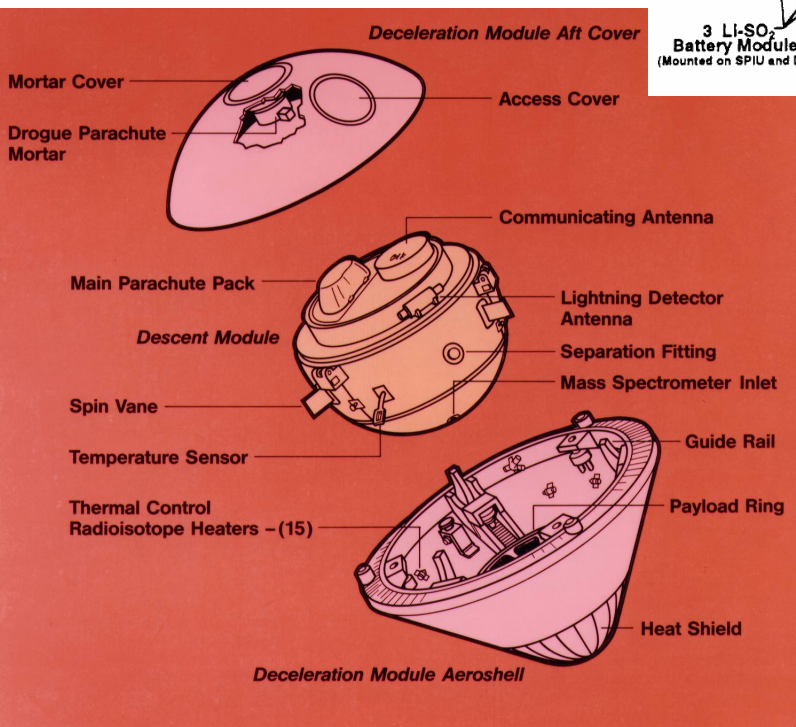
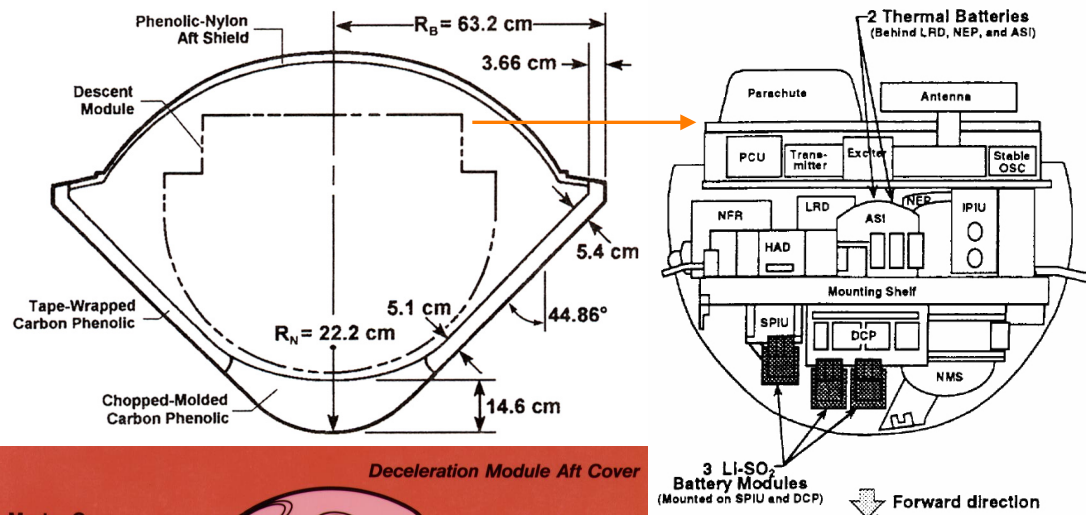
Flyby + Relay telecom based architecture can be supported with **batteries**, with **LILT solar panels for backup** during non-mission critical modes

Power systems for an orbiter architecture can be **significantly more challenging** and the feasibility should be assessed accordingly



Key Mission Drivers for the Probes

Item / Subsystem	Mass (kg)	Mass Subtotals (kg)
Deceleration Module		221.8
Forebody heat shield	152.1	
Afterbody heat shield	16.7	
Structure	29.2	
Parachute	8.2	
Separation hardware	6.9	
Harness	4.3	
Thermal control	4.4	
Descent module		117.1
Communications subsystem	13.0	
C&DH subsystem	18.4	
Power subsystem	13.5	
Structure	30.0	
Harness	9.1	
Thermal control	4.3	
Science instruments	28.0	
Separation hardware	0.9	
Probe Total		338.9



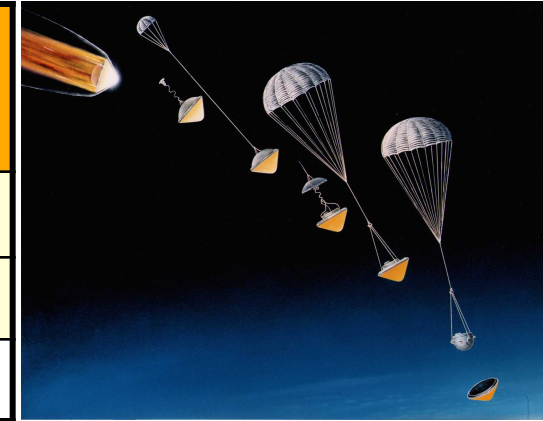
Science Instruments:

(ASI)
Atmosphere structure instrument
(NEP)
Nephelometer
(HAD)
Helium abundance detector
(NFR)
Net flux radiometer
(NMS)
Neutral mass spectrometer
(LRD/EPI)
Lighting and radio emission detector/ energetic particle detector

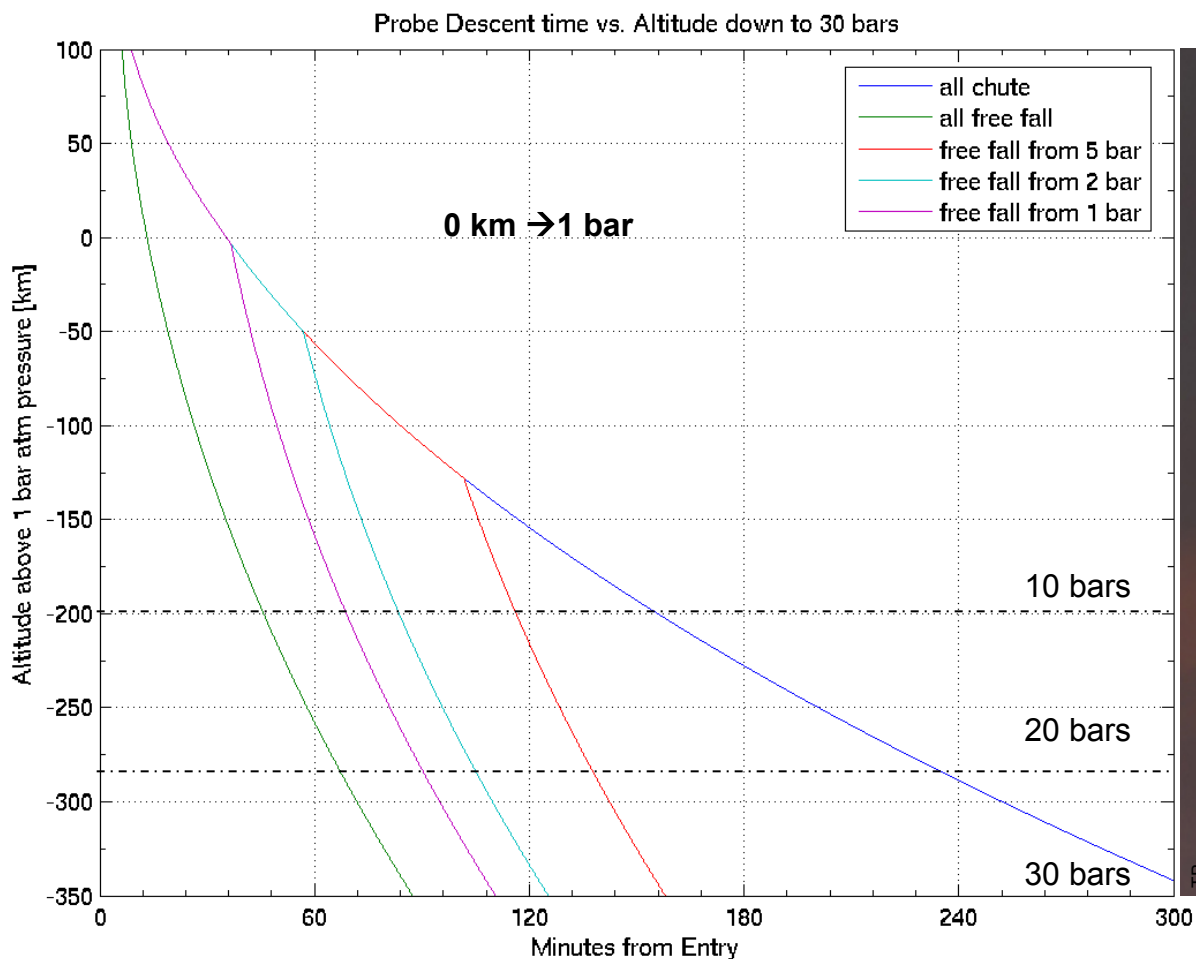
Ref: Galileo Probe Deceleration Module Final Report, Doc No. 84SDS2020, General Electric Re-entry Systems Operations, 1984
AIAA, "Project Galileo Mission and Spacecraft Design", Proc. 21st Aerospace Science Meeting, Reno, NV, January 10-13, 1983

Pre-decisional – for discussion purposes only

Entry direct.	Latitude deg	Rel. entry V, km/s	Max diameter, m	Entry mass, kg	Max. heat rate*, kW/cm ²	Forebody TPS mass fraction	Est. total TPS mass fraction* (+ zero margins)	Max. decel., g
Pro.	6.5°	26.8	1.265	335	2.66	23.5%	25.8%	43.6
Pro.	-45°	29.6	1.265	335	3.67	24.8%	27.3%	47.9
Retro.	6.5°	46.4	1.265	335	21.5	35.2%	38.7%	76.4

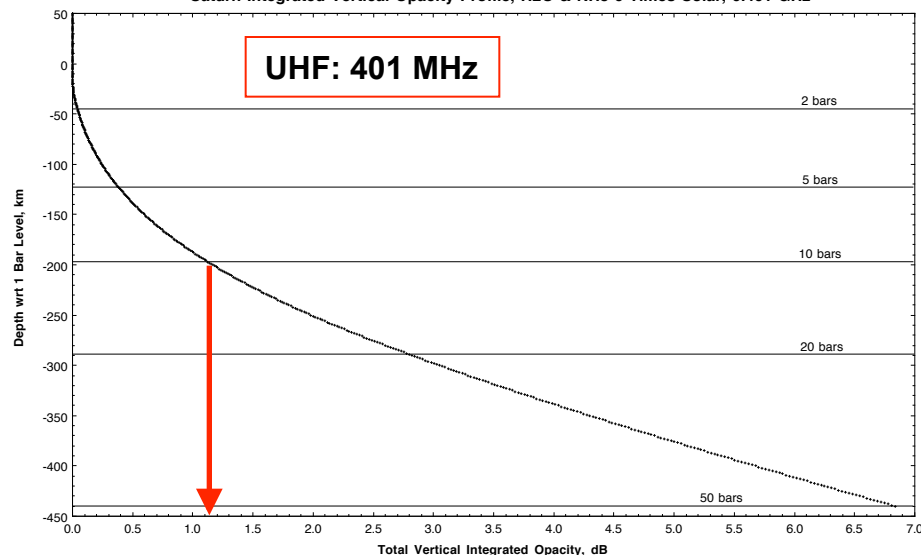


- TPS availability for Galileo size probes H/S were confirmed by NASA ARC
 - C-P for prograde entry can be supported (heating rate about 10% of Galileo's)
 - **Retrograde heat flux** might be **too high to support** with current testing facilities
- **TPS** requirement **at Saturn** is **less demanding** than at Jupiter
- **TPS mass-fractions** for prograde entry is about **30% less than Galileo's**
- **Max. heating** rates and **max. g load** about **35% of Galileo's**
- **Heating pulse** about **2.5 times longer** due to scale height difference
- Saturn probes have **less ablation**, but need **more insulation**
- **Time to parachute deployment** is about **5 minutes**

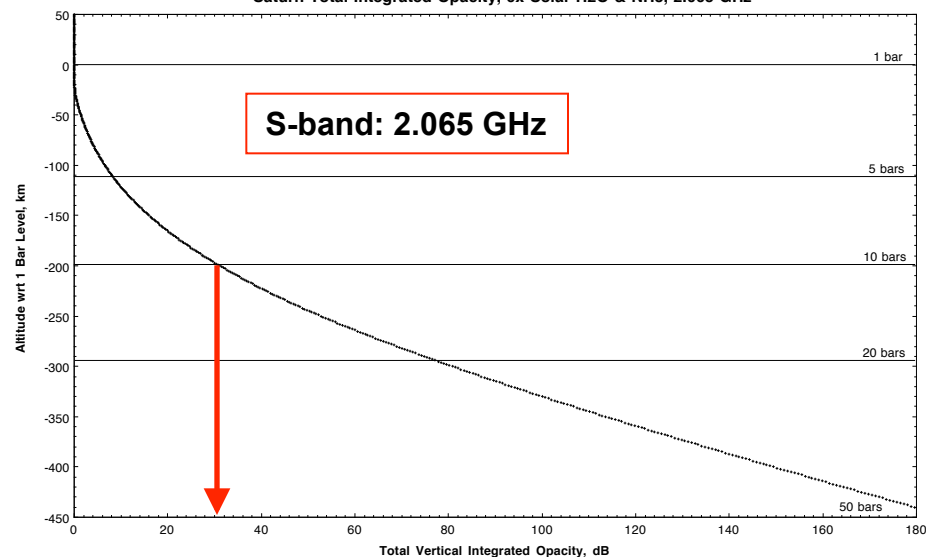


- If **free fall begins at pressure of 1 bar**, it will take **~70 minutes** from entry **to** reach **10 bars**
- For better *probe stability*, the freefall phase could be replaced with *descent with a drogue parachute* (This requires further analysis)
- If the descent is **entirely on the parachute**, it will take **~2.5 hours** to reach **10 bars**

Saturn Integrated Vertical Opacity Profile, H₂O & NH₃ 6 Times Solar, 0.401 GHz



Saturn Total Integrated Opacity, 6x Solar H₂O & NH₃, 2.065 GHz



Ref: Tom Spilkner, JPL, 2006

- Saturn's scale height is
~2x that of Jupiter's
~45 km at the pressures of interest
- Saturn has
 - no radiation environment
 - no synchrotron radiation, thus we can use low (UHF) frequencies
- Zenith attenuation of radio signal as a function of probe depth (measured by atmospheric pressure), based on concentrations at 6 times solar abundances

Attenuation (w/o margin) at p=10 bar

UHF (400 MHz): ~1.2 dB

S-band (2 GHz): ~31 dB

Data rates

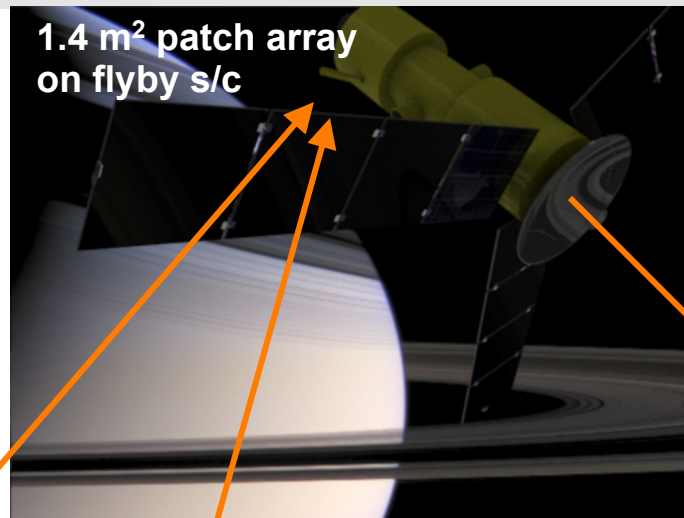
Probe 1: 1024 bps (~3.7Mb)

Probe 2: 512 bps (~1.9Mb)

Data volume

Total from 2 probes: ~6.3Mb

1.4 m² patch array
on flyby s/c



35W X-ban DTE for
science and telemetry
3 m HGA for downlink
(MGA & LGA emergency links)



Frequency:

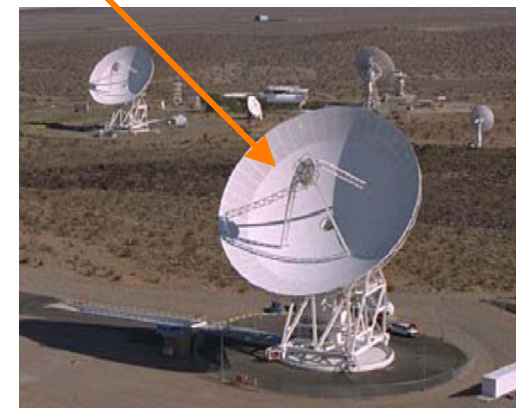
UHF 401 MHz

Antenna:

UHF **LGA**

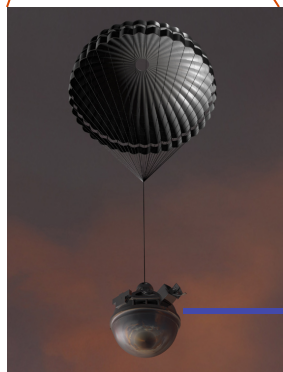
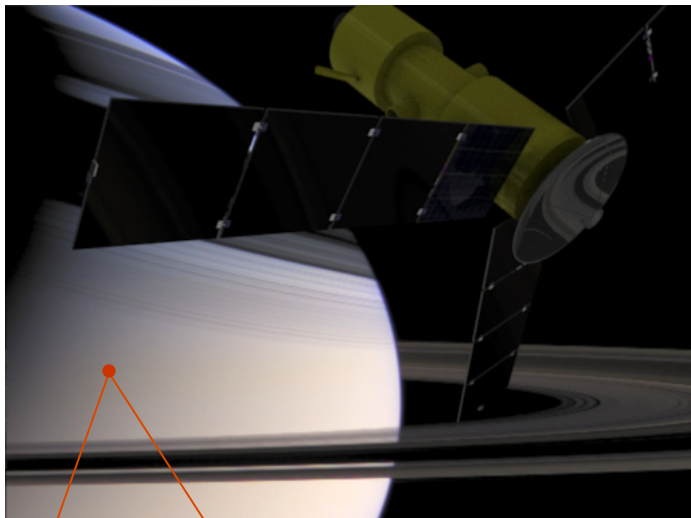
Probe hardware:

Electra-lite (20W)



34 meter DSN

- “Store and dump” operation
- Probes has **NO** line of sight with Earth
- All data downloadable within the **first two hours** of a single tracking pass



DTE Telecom feasibility is influenced by:

- Probe telecom power
- Probe antenna size
- Probe antenna design
- Ground antenna size
- Separation distance
- Atmospheric absorption
- Solar plasma
- other link losses

Low frequency (e.g., UHF is required to mitigate atmospheric absorption)

Conventional telecom design / configuration explored in these studies did not support DTE telecom!

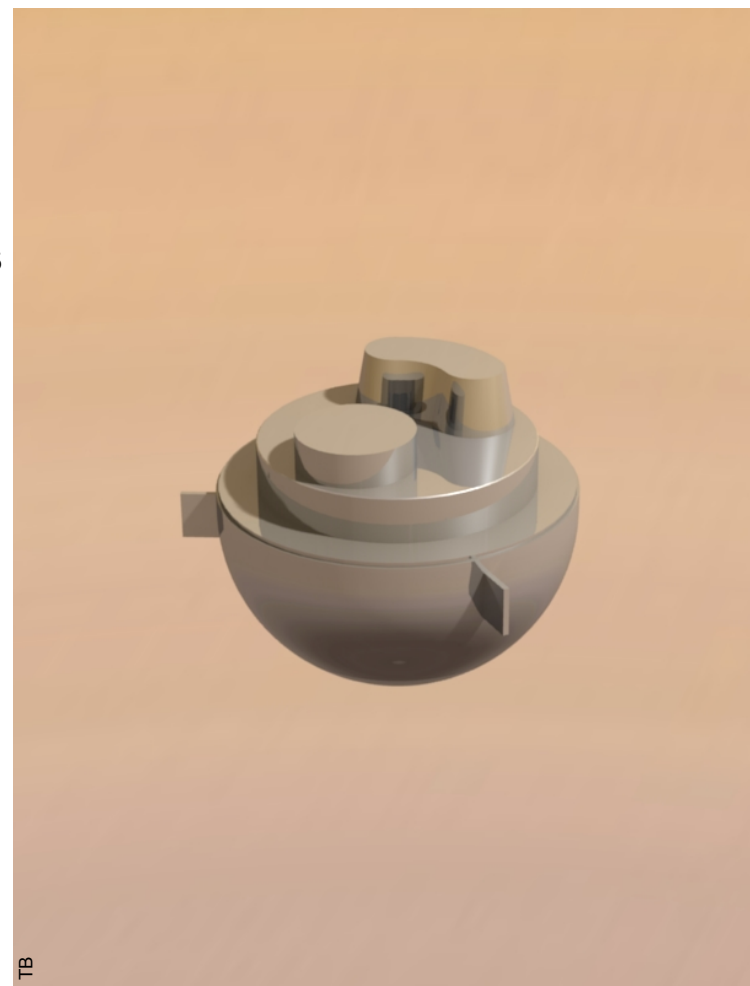


LARGE ground based UHF antenna arrays are required

Unconventional telecom design for DTE could be explored in future studies.

A solution – if exists – may require new component designs & qualification of telecom system elements

- **Assume / use** mission, instrument and design **heritage** when possible, for example:
 - Galileo probe (instruments, power system (batteries), descent module)
 - TPS (use existing material (carbon phenolic) from NASA ARC)
 - Juno (LILT solar panels, microwave radiometer)
 - Electra (telecom from Mars Program)
- **Minimize** science **instruments or instrument cost**
 - Descope towards **minimum science** requirements
 - Allow for **contributed instruments**
- **Simplify** mission **architecture**
 - Shorter flight times **reduce operations costs**
 - Use a **flyby** instead of an orbiter
 - Drop down in **Launch Vehicles** (by minimizing spacecraft mass)
 - Use **identical probes**



- **NASA funded studies** in support of NASA's SSE Roadmap and Planetary Program Support activities, **proved the feasibility of a NF class Saturn probe mission**
- A **number of mission architectures** could be suitable for this mission, e.g.,
 - **Probe Relay** based architecture with short flight time (~6.3-7 years)
 - **DTE probe telecom based** architecture could be assessed by the flight time is expected to be significantly longer (~11+ years – TBD),
 - Probes decoupled from the carrier, allowing for polar trajectories / orbiter.
 - Past studies proved this option not feasible, but unconventional telecom approaches may prove to be useful.
 - **Orbiter** would likely impact mission cost over **flyby**, but would provide significantly higher science return
- The Saturn probes mission is **expected** to be identified **in NASA's New Frontiers AO**
- Thus, **further studies are recommended** to refine the most suitable architecture
- **International collaboration** is started through the KRONOS proposal work under ESA's **Cosmic Vision** Program

